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Early Phase Detection and Coverage of Extragalactic and Galactic Black Hole X-ray Transients with the SKA

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SKA's large field of view and high sensitivity at low frequencies will provide almost a complete coverage of the very early rising phase of extragalactic and Galactic transients which undergo a flare or outburst due to an abrupt accretion onto either supermassive (such as tidal disruption events, TDEs) or stellar mass black hole transients (such as black hole LMXB) , when their broadband emission is supposed to be jet-dominated at low luminosities, allowing SKA to be the first facility to make source discoveries and to send out alerts for follow-up ground or space observations as compared with the sensitivity of future X-ray wide-field-view monitoring. On the other hand, due to extremely large rate-of-change in the mass accretion rate during the rising phase of TDE flares or transient outbursts, SKA will be able to cover an extremely large range of the mass accretion rate as well as its rate-of-change not accessible with observations in persistent black hole systems, which will shape our understanding of disk-jet coupling in accreting black holes in the non-stationary accretion regimes.

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1. Scientific background

Wide field-of-view (FOV) astronomical monitors and survey telescopes are very important to the time-domain astronomy, a rapidly developing field with the advances of space and ground telescopes equiped with either fast response or wide FOV monitoring or survey capabilities across a broad range of the electromagnetic wavelength. Diverse time domain phenomena, such as gamma-ray bursts, supernova explosions, tidal disruption flares, X-ray nova, giant flares from soft gamma repeater, transient pulsars or fast radio bursts, and so on, can only be efficiently detected with sensitive monitoring or wide FOV surveying telescopes. Wide FOV monitoring and surveying telescopes will bring a great impact on future astronomy.

All-sky or wide FOV X-ray monitoring has led such time domain studies on high energy transients for several decades. The success can be dated back as early as the discovery of gamma-ray bursts which was about 50 years ago. Current X-ray monitors remain at the frontier of time-domain astronomy on high energy transients. For instance, new scientific discoveries continue to occur from monitoring or survey observations made with space observatories such as Swift, MAXI, and INTEGRAL. However, newly built or currently planned multi-wavelength time-domain ground facilities, such as the Palomer Transient Factory (PTF), the Pan-SSTARs, the LSST, and the LOFAR etc., will bring time domain astrophysics to a golden era, allowing almost simultaneous broadband coverage of those transient events, including potential transient events associated with strong gravitational waves. Here we emphasize that wide FOV monitoring observations with the SKA have significant advantages in observing Galactic and extragalactic black hole transients in the early rising phase, and have a great potential to take over future space X-ray monitors in monitoring Galactic and extragalactic black hole transients based on what we have learnt about disk and jet emission from accreting black holes and neutron stars. A wide FOV monitoring towards the central Galactic bulge region in the SKA1 can demonstrate these advantages in the early phase of SKA.

1.1 Monitoring of Extragalactic and Galactic X-ray transients

Most of the high energy transients, such as GRBs and black hole transients, are of the nature of rapid accretion onto compact objects in a large range of mass accretion rate, from below 10^{-5} Eddington luminosity to super-Eddington luminosity. X-ray monitoring observations in the past few decades have usually reached a daily sensitivity of mCrab level, unable to alert transient activities at earlier times when the X-ray flux is substantially lower. At lower mass mass accretion rate regimes, the observed electromagnetic flux is probably dominated by jet emission rather than from the emission of the accretion flow itself, as suggested by the observations of microquasars and the prediction of the accretion theory such as advection-dominated accretion flow (ADAF) model for the accretion flows in the lower mass accretion rate regimes (Esin et al. 1996). This unambiguously highlights that the most sensitive and effective probe of activities in black holes accreting at low mass accretion rate is through the observations of their jet emission. Observations have shown that jet emission in microquasars contribute to a broad wavelength from the infrared (e.g., Russel et al. 2007) all the way up to at least ultra-violet (e.g., Yan & Yu 2012; Degenaar et al. 2014). However, these jets are usually detected in the radio band since only the most energetic ones could extend to shorter wavelengths. This makes sensitive radio observations the most promising probe of the activities of black holes accretion at low mass accretion rates.

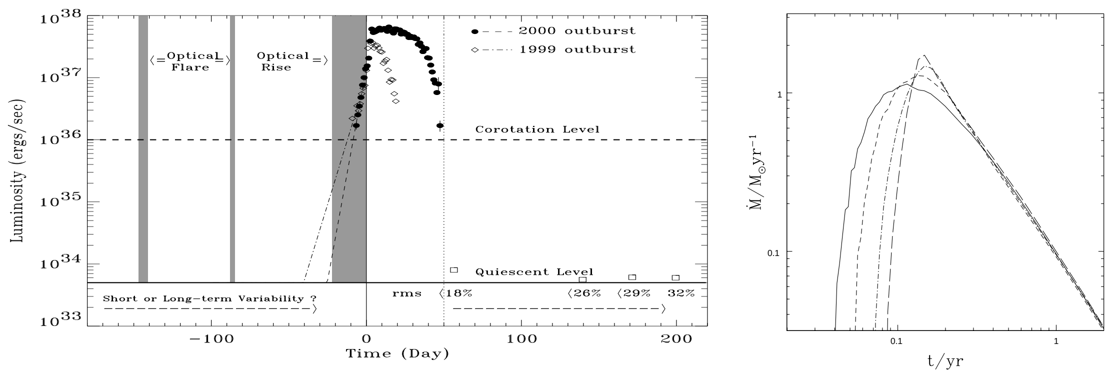

Figure 1: Examples of X-ray outbursts from a Galactic X-ray binary transient and the evolution of the fall-back rate expected from theory during typical tidal disruption events (TDEs). **Left:** An example of the X-ray outbursts of the neutron star soft X-ray transient Aquila X-1 as observed with the RXTE/ASM (2–12 keV). Typical rise time scale for black hole transients are about twice longer. A linear extrapolation of the rising trend in the X-ray flux back in time implies that outbursts started about 10–30 days from quiescent level before they were detected by the ASM on board the RXTE. Future X-ray monitoring with Lobster-Eye instrument would reach an X-ray sensitivity at the level of an X-ray luminosity of about 5×10^{34} ergs/s for this source, while SKA1 and SKA2 will be able to monitoring this source immediately after the source rises from quiescence, at the equivalent X-ray luminosity level of 1×10^{34} ergs/s (corresponding to about 25 microJy in radio band at 8.5 GHz) following the trend established from previous observations of a slope 0.6 (Miglari et al. 2011), and can detect such outbursts about a week before any possible detections with the next generation all-sky monitors, leading to a major step forward for the broadband monitoring of Galactic XRB transients. **Right:** The evolution of fall-back rate during typical tidal disruption flares (from Lodato, King & Pringle 2009). The typical rise time is on the time scales of about 20 days (0.5 T_m as calculated in Evans & Kochanek 1989) and the rate-of-increase of the mass accretion rate onto the supermassive black hole would be dramatic. Towards lower fall-back rate back in time during the rising phase, jet emission is expected to dominate when the corresponding mass accretion rate is low (Yuan, Cui & Narayan 2005). The SKA 2 has the sensitivity and large-enough FOV to detect these events about a week before they reach the maximum fall-back rates. Since typical peak luminosity of a TDE flare will be super-Eddington for typical SMBHs of the order of 10^6 solar masses, the coverage of almost the entire rising phase with the SKA 2 will be revolutionary.

Besides observing transients in the radio wavelength, there are quite some ambitious optical surveys with large FOV telescopes undergoing or planned, which will bring significant progress on transient science. Among them, iPTF has carried out optical survey with different cadences, from a 5-day cadence down to 90 seconds. Its followup project ZWICKY will have a FOV of 47 square degrees with a survey speed of 3760 square degrees per hour. In its survey mode, Pan-SSTARS will cover 6000 square degrees per night, reaching a limiting magnitude of 24 in each exposure of tens of seconds. On the other hand, LSST has a field-of-view of 9.6 square degrees and will detect 10^6 transients per day. All these survey telescopes will bring tremendous optical data on transients and persistent sources. SKA's monitoring and survey capability provide opportunities for source discoveries and synergetic multi-wavelength campaigns on newly discovered transients and persistent sources.

2. New discovery window with the SKA: the early rising phase

Space X-ray monitoring has been extremely successful in the past few decades on high energy transients. Some examples of the discoveries made with X-ray monitoring observations include gamma-ray bursts and soft gamma repeaters, soft X-ray transient outbursts, supernova explosions during shock breakout, jetted tidal disruption events, etc. Most often these all sky or large FOV X-ray monitors are onboard satellites or space stations with a typical earth orbit of 1.5 hours or so, and usually serves to send out alerts while detailed X-ray spectral and short-term variability can not be simply acquired. Detailed spectral and timing properties rely on follow-up target-of-opportunity observations with dedicated space or ground telescopes or experiments. In the past decades, space X-ray monitors have reached a daily sensitivity at the mCrab level. In the next decade the sensitivity of X-ray monitors would reach a flux level of about two orders of magnitude lower, with the development of large field-of-view Lobster-eye X-ray optics (Schmidt 1975; Angel 1979).

When approaching black hole transients at lower luminosities, large FOV radio facilities like SKA, in phase 2, will impose major challenge to the role of X-ray all-sky of wide FOV monitoring, and will likely take the lead instead according to our current knowledge of black hole accretion at low luminosities. Gallo et al. (2003) showed that there is a correlation between the radio flux and the X-ray flux in black hole X-ray binaries in the hard state, with the power-law index of the radio flux being 0.7 of that of the X-ray flux. The most updated data shows some obvious deviation and large scatters from this correlation (e.g., Gallo et al. 2014). However, black hole transients are still much more radio loud than neutron star low mass X-ray binary transients (Migliari & Fender 2006). It is found that in the NS LMXBs the radio-X-ray correlation may follow different pow-law slopes (Migliari et al. 2011). The transient NS LXMB Aquila X-1 is typical for NS LMXBs showing a slope of 0.6, thus the slope for Aquila X-1 type NS LMXBs can be used to give conservative estimate of the LMXB transients as a whole. Together with the overall correlation in black hole X-ray binaries, this implies that the radio flux decrease slower than the X-ray flux when we approach lower luminosities. Therefore opportunities with radio observations will start to arise; sensitive radio observations will be able to surpass X-ray monitoring observations towards lower mass accretion rates. Taking Aquia X-1 as the example (see Figure 1 left). The empirical correlation with a power-law index of 0.6 gives that at an X-ray luminosity of 10^{34} ergs/s, which is just a little above its quiescent luminosity, the corresponding radio flux at 8.5 GHz would be 25 microJy. This radio flux level is well above the sensitivity of SKA1-SUR or SKA1-LOW for 20 minutes observations or so while an X-ray Lobster-Eye instrument can only reach the X-ray luminosity level of 5×10^{34} ergs/s with similar exposure time, which means the next generation X-ray monitor is not able to detect it in the same period of time. The same applies to accreting supermassive black holes. Merloni et al. (2003) found that there is fundamental plane of black hole activity. Similarly, the power-law index of the radio luminosity vs. the X-ray luminosity relation is about 0.6. Again, this indicates towards lower luminosities black hole accretors are relatively more radio bright compared with their X-ray brightness, and therefore radio observations with the SKA1-SUR or SKA1-LOW, and SKA2, will be more sensitive to source activities at low luminosities (see Dewdney et al. 2013 for the SKA1 parameters). This means SKA observations in radio is able to lead X-ray monitoring campaigns on black hole transients of both Galactic

and extragalactic origin. Sensitive wide FOV monitoring in radio band with SKA hence opens a new discovery window inaccessible with the X-ray monitoring of both stellar mass black hole and supermassive black hole transients in the decades to come.

For stellar mass black hole transients in our Galaxy, the quiescent X-ray luminosity in the 0.5–10 keV band is about 10^{30-31} ergs/s (e.g., Garcia et al. 2001). During the rising phase of black hole or neutron star LXMB transient outbursts, the e-folding rise time scales in the X-ray band measured with current X-ray monitors is about 3-5 days (Yan & Yan 2014, see early results of X-ray monitors in Chen et al. 1997). With an equivalent X-ray sensitivity of 1-2 orders of magnitude better, the SKA1 (and the SKA2) design will be able to send out alerts of black hole transient outbursts about a week ahead of X-ray monitoring detections if we assume the rises of outbursts are of a simple monotonic form. This can be seen in an example shown in Figure 1. Similarly, extragalactic black hole transients such as tidal disruption events (i.e., solar-like star disrupted by previous dormant supermassive black holes at the centers of normal galaxies) should also start to accrete matter from the debris flow of a disrupted star from very low mass accretion rate to super Eddington rate (Rees 1988; Evans & Kochanek 1989; Lodato, King & Pringle 2009), although the exact accretion process in the early stages is yet not well-studied. According to simple theoretical estimates, the fall-back rate increases from quiescent level to super-Eddington fall-back rate up to more than 100 Eddington rate in about two-week's time during the rising phase of typical TDE flares (Rees 1988; Evans & Kochanek 1989; Lodato, King & Pringle 2009). Taking a conservative estimate of the quiescent luminosity level of supermassive black holes at centers of normal galaxies as 10^{34} ergs/s (note: Chandra observations of the supermassive black hole source Sgr A* at the center of our Galaxy gives such a value, see Baganoff et al. 2003; Nelsen et al. 2013), the mass accretion rate would rise by up to 10 orders of magnitude in about two weeks' time (Evans & Kochanek 1989). The e-folding rise time scale is then on the time scale of about 0.5–2 days, which can be ten time shorter than those seen during the rising phase of outbursts from Galactic black hole LMXB transients. Therefore TDE flares are cases of non-stationary black hole accretion in the extreme.

SKA has a very large field of view. For example, at 1 GHz, its field-of-view of SKA2 is around 200 square degrees. Both SKA1 and SKA2 are also very sensitive. For instance, SKA1-SUR's 20 minute sensitivity at 1 GHz is at 0.01 mJy level, and SKA2's 20 minute sensitivity at 1 GHz is at the μJy level. Due to its high sensitivity, its convenience for observations of our Galaxy and its large FOV, SKA is the best astronomical facility to catch the rising phase of outbursts or flares from accreting stellar mass black holes and supermassive black holes. Little is known about the early rising phase of these outbursts or flares from previous observations due to insufficient sensitivity of current and past space X-ray monitors. SKA1-SUR and the SKA Phase 2 will open a huge discovery window in catching the very early rising phase of those black hole transient flares and outbursts, including both black hole binary transients and tidal disruption flares. Our estimates based on current knowledge of soft X-ray transient outbursts and TDEs suggest that SKA1, through a dedicated Galactic bulge program, is able to detect black hole binary transients in our Galaxy; while SKA2 is able to detect extragalactic tidal disruption events during the early rising phase about a week ahead of the most sensitive X-ray monitors in the next decades (see Figure 1 left and right).

3. Accretion physics and jet activity in extreme non-stationary accretion regimes

Observations of X-ray spectral states in Galactic X-ray binaries have shown that the primary parameter - the mass accretion rate is not the only parameter which drives spectral state transitions (Miyamoto et al. 1995; Homan et al. 2001; Maccaroni & Coppi 2003). The hard-to-soft spectral state transition usually observed during the rising phase of outbursts actually occurs at luminosities which correlates with the peak flux of an outburst or flare (Yu et al. 2004; Yu et al. 2007; Yu & Dolence 2007), due to the rate-of-increase in the mass accretion rate, which is not negligible, and in most of the spectral state transitions seen in bright Galactic X-ray binaries the effect of the rate-of-change of the mass accretion rate on the transition luminosity dominates (Yu & Yan 2009; Tang, Yu & Yan 2011). These studies indicate that the accretion properties are set up early, and one can predict spectral state transition ahead of time by measuring the rate-of-increase of the X-ray luminosity (Yu & Yan 2009). It is worth noting that our current knowledge of accretion regimes are actually based on stationary accretion theories. Non-stationary accretion regimes are largely not explored. The studies of the hysteresis effect implies that there is actually a non-stationary accretion regime, e.g., the black hole hard state regime corresponding to non-stationary accretion which exists above the mass accretion threshold below which the classical hard state sits as explained by existing theory (e.g., Esin et al. 1997). Because there is certain complex correlation between the radio flux and the X-ray flux in the hard spectral state (Gallo et al. 2003; but with so-called outliers), there is also evidence that non-stationary accretion plays an important role in powering the radio jet. This is suggested by a possible detection of the correlation between the rate-of-change of the mass accretion rate and the episodic jet power (Zhang & Yu, 2014, see Figure 2). Since both TDE flares and black hole binary transients can be detected by the SKA at much earlier times and at much lower luminosities, SKA will provide the opportunity to probe jet activity in the non-stationary accretion regimes over a radio flux range by more than 4 orders of magnitude, which roughly corresponds to an X-ray flux range by about 7 orders of magnitude in the Galactic black hole transients. Stronger effect of non-stationary accretion is expected in extragalactic X-ray transients associated with tidal disruption events due to their much shorter e-folding rise time scale. Our conservative estimate suggest that TDE flares can rise in luminosity as large as 10 orders of magnitude on the time scale of 20 days, accompanied by an extremely large rate-of-change of the mass accretion rate inaccessible in other black hole systems.

4. Recommended campaigns on extragalactic and Galactic black hole X-ray transients

As we described above, wide FOV sensitive observations in the radio wavelength have great advantages in detecting stellar mass and supermassive black hole X-ray transients during the very early rising phase of their outbursts or flares. Using SKA1-SUR band 2 with a FOV of 18 and a sensitivity of 0.351mJy/s$^{-1/2}$, in order to reach 0.01 mJy/beam per field, we would need 20.5 minutes observation. The predicted SKA2 sensitivity is about 10 times sensitive than SKA1, which means we can reach the same sensitivity per field in only 12 seconds. With an increased FOV of SKA2, an all-sky survey down to 0.01 mJy/beam per field is applicable.

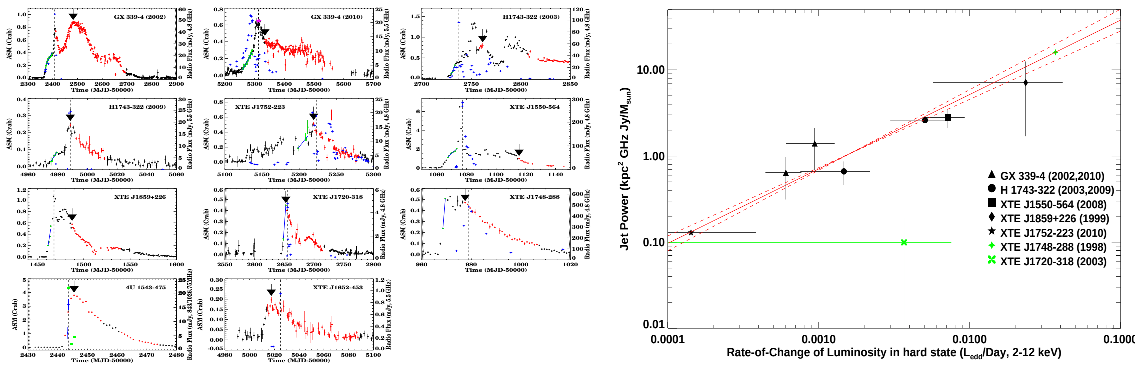

Figure 2: Evidence of the role of non-stationary accretion on the power of episodic jets in microquasars (figures adapted from Zhang & Yu 2014). **Left:** X-ray outbursts of black hole transients with radio observations of the episodic jets. Data shown in blue are radio measurements, data shown in red correspond to black hole soft state. Data marked in green correspond to the segments from which the rate-of-increase of the X-ray luminosity is measured for the rising phase of the corresponding outburst. **Right:** The relation between the episodic jet power and the rate-of-change of the X-ray luminosity measured before the hard-to-soft state transition during black hole transient outbursts (see Figure on the left). The dark points corresponding to sources with good measurements or estimates of mass, distance, X-ray and radio fluxes, while the green points indicate sources with large uncertainties.The best curve is over-plotted in red, with the ranges of uncertainty shown as dotted lines.

In Phase 1, SKA1-SUR has a FOV of about 18 square degrees in PAF band 2. For Galactic black hole or neutron star transients, in order to cover the very early phase of any future outbursts of Galactic black holes as well as neutron star LMXB transients, most of which reside in the Galactic bulge, a dedicated monitoring campaign of the Galactic bulge is recommended on the daily basis with the SKA1-SUR at 1 GHz. Past X-ray observations of the Galactic bulge indicate that there are about 80 known persistent and transient X-ray binaries in the central 25 x 25 degrees of the Galactic bulge, and probably hundreds to discover in the future. In a smaller central Bulge region of 8 x 8 squared degrees, there are 35 known persistent and transient X-ray binaries. In order to cover this region, we recommend that SKA1-SUR performs more than 4 short observations of the 8 x 8 square degrees of the Bulge down to 0.01 mJy flux level. According to the empirical relation established from radio flux vs. X-ray flux correlation, these SKA1-SUR observations will be able to detect outbursts of Galactic black hole or neutron star LMXB transients before they are visible to current or future X-ray monitors, and will be especially successful in detecting accretion-powered millisecond pulsars which is usually radio-louder than the Atoll type neutron star LMXBs. After the implementation of the full version of the SKA, because the FOV would reach 200 square degrees at 1 GHz, three observations will be able to cover the central Bulge region.

With full SKA's capability of a FOV of about 200 square degrees, SKA is a powerful machine to detect new tidal disruption events at very early times. This will bring tremendous opportunities for Target-of-Opportunities (ToO) with space X-ray observatories such as Athena+ and ground optical telescopes on the scale of tens of meters, since there will be plenty time for both ground and space observatories to respond (about 10 days' earlier than current X-ray monitoring can provide), which will push time domain astrophysics on black hole transients, especially the tidal disruption

events, to the extreme regimes. However, there are difficulties for the SKA1-SUR or the SKA1-LOW to sufficiently detect some extra-Galactic transients such as tidal disruption events due to their limited FOV, but still there are occasions when tidal disruption events occur in the SKA1-SUR or the SKA1-LOW's FOV. A better strategy during SKA1 for black hole transient science is to use SKA1-SUR and SKA1-LOW to perform quasi-simultaneous observations of the same field of view of optical surveys or X-ray all-sky monitoring, such as the LSST's FOV as much as possible. In this way, due to broadband measurements, empirical classification of transient events could be made straight forward. This would allow SKA-MID to perform sensitive follow-up observations of some candidate tidal disruption events timely.

In summary, the motivations of SKA1 and SKA2 campaigns on Galactic and extragalactic black hole X-ray transients are 1) the coverage of the very early rising phase of outbursts or flares and sending out extremely early alerts; and 2) rather complete coverage of jet activities in the non-stationary accretion regimes corresponding to a large range of the mass accretion rate and its rate-of-change, which are inaccessible in other accreting black hole systems.

5. Scientific outcomes of SKA1 and SKA2

We expect the following outcomes of the SKA1 and SKA2 on the science of black hole transients containing both stellar mass or supermassive black holes.

In the SKA1, a Galactic bulge monitoring campaign with SKA1-SUR in the central 8 x 8 squared degrees for 1.5 hours on the daily basis will be able to cover the very early rising phase of nearly half of the stellar mass black hole and neutron star LMXB transient outbursts, which will lead the detection in the X-rays by sensitive X-ray monitoring observations. Such a Galactic bulge campaign will also detect some APMSP outbursts. Such a monitoring campaign will answer how jet is powered in the non-stationary regimes in a large range of mass accretion rate at the same time of the significant rate-of-change in the mass accretion rate, which will address accretion and jet physics in the non-stationary accretion regimes in LMXB transients. The program will also make SKA1-SUR likely the first facility to detect new black hole and neutron star LMXB transients in the Galactic Bulge at unprecedented low flux level and will be able to send out alerts on new BH or NS transients or outbursts to other ground or space observatories. On the other hand, only coordinated or follow-up SKA1 observations of extragalactic TDE flares are possible in SKA1.

In the SKA2, an efficient monitoring of the Galactic bulge of a 25 x 25 FOV can be achieved at 1 GHz. Additionally, SKA2 will provide the best opportunity to study extragalactic SMBH transients such as TDEs. The most significant scientific impact on the study of black hole transients would come from the detection of a lot extragalactic TDE flares in the early rising phase with SKA. The SKA2's sensitivity allows detections of such events at the very early times, which is mostly unknown in both theory and observation. SKA2 would provide a complete coverage of their jet activities over an extremely large range of mass accretion rate and its rate-of-change, and is able to send out alerts extremely early for the largest ground and space observatories to respond. Thus SKA will provide the golden opportunity to solve important astrophysical questions associated with black holes transients in binaries and at the centers of normal galaxies.

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